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ABSTRACT

This report provides a nontechnical summary of a series of studies from a research project with three major foci: memory storage dynamics, memory retrieval dynamics, and coding in semantic memory. A theory of forgetting was developed, involving time and interference factors. Memory traces have two properties: strength and fragility. Consolidation involves a reduction in fragility that occurs continuously and reduces the rate of time decay. Storage interference from subsequent learning is unaffected by delay since learning; such interference is therefore independent of fragility. Data consistent with the theory were obtained from children, adults, and elderly subjects and from adults in states of sobriety and alcoholic intoxication. Memory retrieval dynamics were studied using the response-signal method of generating speed/accuracy trade-off functions; 14 different theories of recognition memory retrieval were evaluated. Some ideas concerning the structure of verbal semantic memory and image-operational memory were developed. Verbal semantic memory is assumed to have the structure of a predicate grammar with extensive propositional embedding. Image-operator memory is assumed to have an operator syntax with no propositional embedding. (Author/AA)

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FINAL REPORT

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CODING AND DYNAMICS OF MEMORY

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Coding and Dynamics of Memory

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Non Technical Summary

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Coding and Dynamics of Memory
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The project had three major foci: memory storage dynamics, memory retrieval dynamics, and coding in semantic memory. Memory storage dynamics is concerned with forgetting, how fast we forget and the conditions that affect the rate of forgetting. Memory retrieval dynamics is concerned with the process by which we use our memories, with the focus in this project being on recognition memory rather than recall. Recognition memory is concerned with the feeling of familiarity evoked by test material, which is greater for previously learned material than for new material and greater for previous material the shorter the retention interval. Whereas the study of storage and retrieval dynamics is concerned with quantitative aspects of memory, the study of coding in semantic memory is concerned with the quality or structure of memory. The basic questions concern how we store both verbal knowledge about the world (e.g., "a robin is a bird" or "department stores are generally not open on Saturday night") and our nonverbal memories (e.g., the image of one's living room, the internal map of one's home town).

Memory Storage Dynamics

Single Trace Fragility Theory

A new theory of memory dynamics was developed on the project. The theory assumes forgetting is produced by two factors: passive temporal decay and interference from subsequently learned material. Memory traces are assumed to have two basic properties, strength and fragility. The greater the strength of a memory trace, the greater the probability of correct recall or recognition. Fragility has no direct effect on the probability of correct recall or recognition, but fragility determines the susceptibility of the trace to the time-decay process. Fragility is the susceptibility of the trace to the spontaneous metabolic or neural activity factors that produce decay of memory. The greater the fragility of the trace, the greater the rate of time decay. Consolidation is an hypothetical unconscious process that takes place during the retention interval (after the period of formal study). According to the theory, consolidation does not increase the strength of the memory trace in storage, but acts to reduce its fragility. At the time of learning, the acquisition process establishes a memory trace with an initial degree of strength and an initial degree of fragility, both of which decline over time. The theory predicts a basic retention function of the following form:

$$m = \lambda(1 + \beta)^{-\psi} e^{-\pi t}$$

where m stands for the strength of the memory trace at time t seconds following learning, λ stands for the degree of learning at time 0 (strength of the memory trace immediately after learning at t=0 seconds), β and ψ are the rate parameters for the time decay process, and π is the rate parameter for the interference process and is proportional to the similarity of

subsequent material to the originally learned material.

Retention Functions

A retention function is the plot of some measure of the strength of the memory trace as the dependent variable as a function of the time decay that has elapsed since the end of learning. Although there have been some sporadic reports of temporary increases of memory strength with increasing retention intervals (reminiscence), this is not consistently observed, at least for recognition memory. We have concentrated on recognition memory rather than recall, because recall is much more affected by a variety of interference factors at the time of retrieval that distort the measurement of the strength of the underlying memory trace. Recognition is much less or not at all affected by these retrieval interference factors and thus provides a purer measure of the strength of the memory trace in storage. A typical memory retention test consists of presenting an item (word, word pair, sentence, picture, etc.) and asking the subject to decide "yes" or "no" regarding whether that item was presented previously in the experiment. The strength of the memory trace is determined by the accuracy with which the subject makes these recognition memory decisions.

The results of hundreds of such experiments determining retention functions for different individuals, for different types of materials ranging from nonsense verbal material to sentences to pictures, studied under various rates of presentation and other conditions during both learning and retention, have produced retention functions that have the form predicted by the theory. Furthermore, the rate parameters for the time decay process are relatively constant over different subjects, material, and conditions. It is strongly confirming of the present theory that structural memory for the exact words or syntax of a sentence have the same form of retention function as memory for the meanings of sentences. Memory for meaning is assessed independently of the exact wording or grammatical structure of the sentences by using a test sentence that is a paraphrase of the originally presented sentence. Furthermore, this same form of retention function appears to hold both for verbal memory and non-verbal memory including memory for pictures and the pitch of tones.

Furthermore, fragility theory appears to eliminate the need to assume separate short-term and long-term memory traces. Because memory for some types of information (such as telephone numbers you have just looked up in the phone book) are forgotten so rapidly, many memory theorists have assumed that two qualitatively different types of memory must be assumed: short-term memory and long-term memory. Fragility theory provides a single trace explanation for why memories are sometimes rapidly forgotten and at other times last for hours, weeks, months, or years. The explanation has two parts:

First, to the extent that what is learned has a high degree of similarity to material that will be processed in the retention interval, the rate of forgetting due to the interference factor will be large compared to the rate of forgetting due to the time decay factor. When this is true, forgetting will be dominated by the exponential decay function characteristic of the interference factor and will be rapidly lost. By contrast, when coding of the material is sufficiently distinctive so as to minimize interference between previously encoded memory and subsequently presented materials, then the form of the retention function is dominated by the power function characteristic of the time decay processes and forgetting will be much more gradual.

Second, even when interference is low and forgetting basically follows the power function, the nature of the power function characteristic of time decay is such as to introduce an enormous amplification between the degree of learning and the useful lifetime of a memory trace. For example, differences in the initial degree of learning of a factor of 2 do not cause material to be remembered twice as long. Rather such a difference causes material to be remembered 10^2 times as long. Thus, a factor of 2 in the degree of learning causes a difference of approximately 100 in the useful lifetime of the memory trace. Since different memories appear to last for all different periods of time, just such an amplification factor would appear to be necessary in order to explain the tremendous diversity in the longevity of different memory traces.

Retrograde Amnesia

After serious head injuries that produce concussion, people frequently experience loss of memory, termed retrograde amnesia, for periods ranging from a few seconds or minutes prior to the injury up to periods of hours, days, weeks, or even years prior to the injury. According to the clinical characterization of retrograde amnesia, it is not the weakest memory traces that are lost, nor the strongest, but rather the traces most recently established irrespective of strength. The tendency to lose the most recently established memories in retrograde amnesia has been confirmed by Larry Squire under more carefully controlled circumstances following electroshock treatment. Occasionally, retrograde amnesia is permanent. More often, the patient recovers most of the lost memory. Recovery from retrograde amnesia also follows the recency principle. That is to say, the first memories recovered are the oldest, with retrograde amnesia gradually shrinking toward the present.

The recency principle of retrograde amnesia provides evidence for a consolidation process in human memory. The extraordinary variability of the temporal extent of retrograde amnesia from periods of seconds to periods of years argues that the consolidation process extends for virtually the complete lifetime of memory traces, rather than being complete in a period of minutes, hours or days. The recency principle of retrograde amnesia indicates the necessity of concluding that consolidation acts on some second property of memory traces such as fragility rather than being an increase in a trace strength.

Recency Judgments

If fragility is a retrievable property of memory traces, then fragility could tell us how long ago a memory trace was established. That is to say, the fragility of a test item could serve as the basis for a recency judgment concerning the time that had elapsed since experiencing that item. This hypothesis was tested under conditions that eliminated mediation of recency judgments by means other than an internal clock and the agreement between the theory and the data was extremely good.

Similarity and Storage Interference

If we form an association between two items A and B, subsequent learning of a new association A-C weakens the strength of association from A to B in memory. In addition to the data collected in support of this unlearning (storage interference) factor on the project, over 20 other studies support

the existence of such similarity-dependent storage interference as measured by means of recognition memory tests. A previous theory concerning forgetting assumed that there was only a single factor producing forgetting, namely, storage interference. The continually decreasing rate of forgetting that is virtually always observed was attributed to a decreasing susceptibility of the trace to interference. However, two important experiments performed on the project provided a definitive contradiction to this previous theory. According to the previous theory, A-C interfering learning that occurred a short time following A-B learning would cause more storage interference than interfering A-C learning that occurred a longer time following A-B learning. The results of the two experiments indicated that the storage interference produced by similar learning occurring during the retention interval was independent of the delay between the original and the interfering learning. It was this finding that led to the assumption of two factors with the decay factor depending on fragility and the interference factor independent of fragility.

Extraexperimental Sources of Interference

The interference theory of forgetting has been dominant in American psychology for probably the last 40 years. Laboratory experiments establish beyond any doubt that interference is a potent factor producing forgetting. But what about the forgetting that takes place outside the laboratory from one session to another? If interference were the only factor producing forgetting, then extraexperimental forgetting should be affected by the same interference factors as affect forgetting produced by experimentally introduced interference. Following this reasoning, Underwood and Postman and their students initiated a number of studies designed to show that learned material that had a higher degree of similarity to material that would be encountered outside the laboratory should have a faster rate of extraexperimental forgetting. However, efforts to obtain such evidence for extraexperimental sources of interference were almost universally unsuccessful. One of the successes of fragility theory is that most of the forgetting occurring outside the laboratory is attributed to the time decay process, and thus exactly such results are expected.

Sleep and Memory

The classic experiment of Jenkins and Dallenbach in 1924 showed that less was forgotten over a night of sleep than over a comparable waking interval. This sleep effect was taken as strong support for interference theory and against temporal decay. However, there are three recent findings that are inconsistent with the interference explanation of the sleep effect and are strikingly consistent with the predictions of the two-factor fragility theory. The findings were not obtained on this project, but the interpretation was. First, the sleep effect is confined to the first half of a night of sleep. That is to say, forgetting is slower over the first half of a night of sleep than over a comparable waking period, but it is not slower over the second half of the night. Second, there is some evidence indicating that the sleep effect is not due to sleep, in and of itself, but rather to the time of day. Subjects that were kept awake during a retention interval at night forgot material virtually as slowly as subjects allowed to sleep during that period of time. By contrast, subjects who slept during the day forgot almost as much as subjects who were awake during the same time of day. Thus, the sleep effect appears to be primarily a time-of-day effect, suggesting an explanation of the sleep effect in terms of a reduction of temporal decay of the memory trace due to changes in metabolic or neural activity factors.

Third, while the delay between original and interfering learning has no effect on the magnitude of interference, several studies have shown that the best retention over a 24 hour period is obtained when sleep occurs immediately after learning rather than being delayed by 8 or 16 hours. This is exactly in accord with the prediction of fragility theory and in striking contrast to the independence obtained when the delay of interfering learning is systematically manipulated.

Effects of Alcoholic Intoxication on Memory

Some introspective reports and experimental studies have suggested that we forget material learned during a period of alcoholic intoxication more rapidly than material learned while sober. However, a study performed on the project indicated that the difference between sobriety and ordinary cocktail-party levels of alcoholic intoxication may be completely a matter of degree of learning, with the subsequent form of the retention function and rate of forgetting being identical for material learned while intoxicated as while sober. The results of a previous study that had suggested a faster rate of forgetting of material learned while under alcoholic intoxication were reanalyzed and shown to be fully consistent with an explanation in terms of reduced acquisition when intoxicated. Thus, it appears that when subsequent memory is poor for the events of the "night before" the explanation is very likely that these events were not very well attended-to and learned originally, rather than that they were forgotten at a faster rate in the interim.

Acquisition Amnesia

Some neurological patients show a very special form of memory deficit consisting of an inability to establish new long-term memory traces. Such subjects may be able to retrieve long-term memories that were established before the onset of the illness or injury that produced acquisition amnesia, but they are not able to establish any new memories after that point. One such patient was studied on the project, and it was demonstrated that the form of his retention function and the rate of forgetting were quite comparable to normal subjects. Once again, the nature of the deficit consisted of a very large reduction in the original degree of learning compared to normal subjects. The rate of subsequent forgetting was approximately the same as normal subjects.

Age and Forgetting

The form of the retention function and the rate of forgetting were studied for the same type of material in subjects of three very different ages: children (averaging 9.5 years), young adults (averaging 21 years of age), and elderly subjects (averaging 68 years of age). The young adults had a substantially superior degree of initial learning compared to elderly subjects who were superior to the children. However, both the forms of the retention function and the rates of forgetting were the same for all three groups. Thus, storage dynamics appear to be invarient with age, at least over this range.

Memory Retrieval Dynamics

Until recently, the only method used to study the temporal dynamics of memory retrieval was the reaction time method. In the reaction time method as applied to recognition memory, subjects would be given a test item and the time for making a "yes-no" decision would be recorded. The conventional reaction time method is subject to a serious problem: speed-accuracy tradeoff. Subjects are typically instructed to respond as quickly as possible making few errors. It has been known for some time that subjects can more-or-less continuously tradeoff decreased accuracy for increased speed by varying some internal speed-accuracy criterion. Until recently, the accuracy levels associated with reaction times in various memory retrieval conditions were almost completely ignored. In view of the enormous opportunity for speed-accuracy tradeoff, such a practice seems indefensible. Accordingly, using an adapted version of a method recently developed to study information processing dynamics in the perceptual area, Adam Reed on the present project was the first to use a new method for studying memory retrieval dynamics: namely, determining speed-accuracy tradeoff functions. Instead of measuring reaction times as the primary variable, subjects are presented with a test item and after varying periods of time are cued to respond immediately "yes" or "no". The subjects' accuracy in responding "yes" or "no" at various manipulated times following presentation of a test item constitutes a speed-accuracy tradeoff function. This function is at chance accuracy until the time intercept, at approximately half a second following presentation of the test item, then it increases to the maximum attainable accuracy over the next two seconds. By examining the form of the speed-accuracy tradeoff function. the time intercept, the asymptote (ultimate accuracy level), and the rate of approaching the asymptote, we hope it will be possible to learn a great deal more about the mechanisms of memory retrieval than have been learned using the reaction time method. I believe we will ultimately have good evidence to support the theory that recognition memory retrieval is basically a direct-access process in which a feeling of familiarity is retrieved over a certain period of time, without the need to search alternative memory locations. However, the data we currently have available are not sufficient to draw such a general conclusion. Indeed the results of one extensive study by Reed, while inconsistent with some search models of memory retrieval, were highly consistent with one particular model developed by John Theios. I believe that the results can be explained by a direct-access retrieval process in conjunction with ongoing rehearsal which undoubtedly occurred under the conditions of that experiment. However, more thought and experimentation will be required to resolve this issue.

Coding and Semantic Memory

The speed-accuracy tradeoff method was applied to three topics concerned with the structure of semantic memory and retrieval therefrom. A study by Albert Corbett studied the structure of memory for a small hierarchical system of concepts concerned with categorizing 12 geometric figures into 4 subordinate concepts and 2 superordinate concepts. The results indicated that memory retrieval dynamics for figures was different from that for figure names. Various theories concerning the representation of concepts were evaluated.

Another study by Barbara Dosher was concerned with the structure of memory for propositions (sentences) in semantic memory. There was some support for the hypothesis that the subject, verb, and object of a proposition

form a nuclear component distinct from a context component consisting of time and location. Retrieval from propositional semantic memory appeared more consistent with a parallel, direct-access process than with a serial search process.

A third study by John Winkelman studied the structure of semantic memory for simple addition facts (e.g., 9 + 7 = 16). The results favored an associative theory over a counting theory, with a node representing an unordered pair, e.g., 9 + 7 = 7 + 9, being associated to a node representing the sum, e.g., 16.

A few interesting ideas were generated concerning the structure of verbal semantic memory as contrasted with image propositional memory. Primarily as the result of studies of brain damaged patients, there is now considerable evidence to support the hypothesis that the cerebral hemispheres of the brain are divided between a verbal modality, located in the left hemisphere for most right-handed subjects, and a non-verbal modality (primarily concerned with spatial images and operations upon those spatial images), located in the right hemisphere for most right-handed subjects. An interesting, but highly speculative, idea generated on the project concerned the fundamental difference in the structural organization of memory in the verbal semantic modality as compared to the image-operational modality.

The theory begins with the hypothesis that the fundamental units of storage in each modality are propositions consisting in many instances of three basic components: subject, verb, and object. According to the theory, there are two fundamental differences between coding in the two modalities: First, organization of a proposition is different for the two modalities. In verbal semantic memory, the verb is first chunked together with the object to form a predicate node and then the predicate node is chunked together with the subject to form the propositional node. By contrast, in image-operational memory, the verb (operator) is first chunked with the subject (input) to form something equivalent to a function node consisting of an operator operating on an input image. The result of this operator applying to an input image is to produce the object (output image). Second, storage in verbal semantic memory has substantial propositional embedding capability. That is to say, a proposition can be embedded as the subject or object of a higher-order proposition, such as "John thinks that Mary hit the ball" or "It is false that John thinks that Mary hit the ball", etc. Of course, images have component parts, but it is assumed that there is no embedding of one proposition in another proposition in image-operational memory. Indeed, if image-operational memory has the sort of component organization specified by the theory, it is not clear that propositional embedding would have any meaning. Of course, these ideas are purely speculative at the present time, and surely wrong in at least some respects, if not fundamentally. However, it seems to me that we need to pass beyond the stage of repeatedly verifying the existence of the two modalities of thought: verbal and non-verbal and proceed to ask fundamental questions regarding the differences in the structure of coding of the mental processes that occur in these two modalities. The present ideas constitute a small step in that direction.